

HIGH Z PARTICLE APOLLO ASTRONAUT DOSIMETRY WITH PLASTICS*

E.V. Benton & R. P. Henke
University of San Francisco, San Francisco
California 94117

On Apollo missions, the individual astronauts' high Z particle exposure is measured by means of Lexan polycarbonate plastic. These layers form one component of the passive dosimetry packets worn in the constant wear garment. They serve as threshold type, high Z, charged particle track detectors, recording only the very highly ionizing particles such as $E < 6 \text{ MeV/amu } ^{12}\text{C}$, $E < 45 \text{ MeV/amu } ^{28}\text{Si}$, $E < 250 \text{ MeV/amu } ^{56}\text{Fe}$, etc. The detectors yield information on the particles' charge, energy, and direction of travel. This data, in turn, is used to obtain the track fluence, the stopping particle density as an integral Z distribution, and the particles' integral LET spectrum. In this paper some of the data gathered on Apollo missions 8-13 is presented.

INTRODUCTION

Recently, considerable interest has been expressed in trying to assess the radiation hazard to astronauts arising from the bombardment by energetic, multicharged particles of cosmic radiation. Although a number of investigators have been interested in this problem for some time, the observation of light flashes by astronauts on Apollo 11 and subsequent missions contributed significantly in focusing attention on this problem. Our interest in this area dates back to 1961 when we started investigating various means of measuring the multicharged particle exposure that astronauts experience in space travel. This has been accomplished on the first lunar orbiting mission, Apollo 8, and all subsequent Apollo missions by means of plastic nuclear track detectors located in the passive dosimetry packets worn by the astronauts.

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MATERIALS AND METHODS

The passive dosimetry packets measuring $5.3 \times 4.3 \times 0.64 \text{ cm}$ consist of a 2-mil - thick FEP Teflon bag which contains 500 mg of LiF (TLD) powder, 600μ thick nuclear emulsions, standard beta, gamma, and neutron - sensitive films, and three 190μ thick layers of type 8070-112 Lexan polycarbonate plastic (Table I). The Lexan layers (about 8 cm^2 in area) are heat sealed at the edges to insure that they remain stationary with respect to each other. The packets are worn by each astronaut in the pockets of the constant wear garment.

The Lexan plastic detectors have several features which make them well suited for heavy particle dosimetry. They are tissue equivalent. Their sensitivity range is such that they are insensitive to singly and doubly charged particles. Consequently, very long exposures of months, or even years are possible to cosmic rays without developing detector saturation.⁽¹⁾

TABLE I

Sequence of layers in the passive dosimetry packet

- Teflon protective pouch
- Thermoluminescence pack
- Black foil wrap of emulsion stack
- Black paper wrap of emulsion stack
- Double component film badge emulsions
- G.5 emulsion
- Lexan 3
- Lexan 2
- Lexan 1
- G.5 emulsion
- K.2 emulsion
- NTA film
- Black paper wrap of emulsion stack
- Black foil wrap of emulsion stack
- Label with number
- Teflon protective pouch
- Astronaut's garments
- Astronaut's body

Perhaps the single most important and unique feature of the detectors is the character of the response as a function of the particles' LET. (2) Both in the unsensitized, and the sensitized form the response varies very rapidly with LET (see Figure 1). This property makes possible the identification of particle charge, Z, even from the relatively short trajectory segments available. The sensitivity of the unsensitized detectors has an effective threshold such that particles with LET below that of about 9 MeV/nucleon, ²⁰Ne ions are not recorded. We use the photo-oxidation technique (3) to sensitize Lexan such that particles with LET above that of about 12 MeV/nucleon, ¹⁶O ions are recorded.

Examples of a calibration curve and tracks are shown in Figures 1 and 2. In Figure 1 is shown the corrected track etch rate, V_T, of 10 MeV/nucleon ¹⁶O, ²⁰Ne, ²⁸Si and ⁴⁰Ar particles. "Corrected" signifies that the effects of UV attenuation in the detector have been removed.

The open and closed points indicate the stability of the calibration from one 40 hr UV irradiation to the next. Etched tracks of 10 MeV/nucleon ¹⁶O, ²⁰Ne, ²⁸Si, ⁴⁰Ar ions are shown in Figure 2. In all four cases the same standard UV irradiation treatment was given with etching performed in 6.25 N NaOH solution containing 0.5% Benax for 2.0 hours at 70.4°C. Four ¹⁶O tracks can be seen, two of them at the approximate center of the photomicrograph.

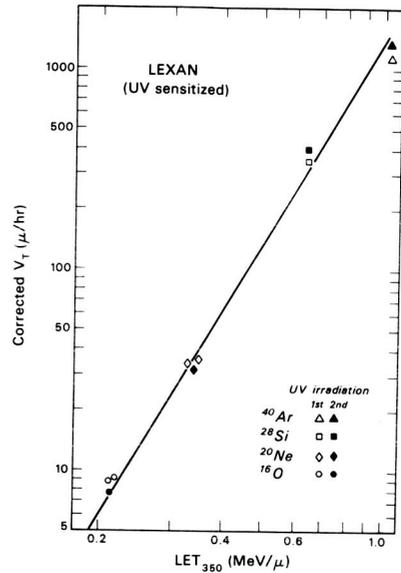


Figure 1. The corrected track etch rate, V_T (microns/hour), as a function of LET (MeV/micron) for four 10 MeV/nucleon particles in Lexan.

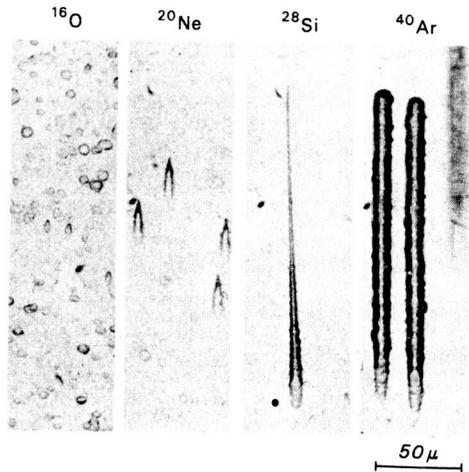


Figure 2. Tracks of four 10 MeV/nucleon incident energy particles in Lexan with etching performed in 6.25 N NaOH solution, containing 0.5 per cent Benax for 2.0 hrs at 70.4°C.

The flight detectors are UV sensitized prior to etching in the same manner as above. The processing is identical to that described above, except that the etch time is 8.0 hours. When processing flight units, calibration tracks, obtained from the Hilac, are always included in the entire processing cycle.

We have investigated a number of techniques for increasing the detector sensitivity. The nature of detector response is such that a small increase in sensitivity increases considerably the number of tracks that are recorded, and hence improves the counting statistics. The use of the UV enhancement technique increases the recorded track fluence by about a factor of 3. Also, it was found that increasing the etch time, from 2 to 8 hours for the sensitized Lexan, produces a further threefold increase in the measured track fluence. However, the extended etch time, together with the UV treatment utilized, result in a considerable deterioration of the detector surface such that many background etch-pits become visible. These in turn, significantly increase the labor required in scanning. Thus the present detector sensitivity is such that the LET required for track registration is just below that of a 12 MeV/nucleon, ^{16}O ion. A further increase in sensitivity of Lexan does not seem likely.

Tracks are located by scanning with an optical microscope usually at 200 X magnification. All detectors are scanned independently by at least two different observers. Measurements are performed at 600 X in each of the surfaces where a visible etch cone is found. Charge identification is accomplished either by measuring the

particle's LET at a given residual range (for particles stopping in the detector), or by measuring the LET and its rate of change with the residual range.⁽¹⁾ From these observations and measurements it is usually possible to determine the particle energy, its direction of travel, and in the favorable cases make charge identification to ± 1 unit of charge.

RESULTS

Some preliminary results from Apollo 8 and 10 Missions have been published previously. A detector worn by astronaut Borman on the Apollo 8 mission was found to contain 0.62 ± 0.11 tracks/cm² of $Z \geq 10$ particles.⁽⁴⁾ On Apollo 10 mission, a detector worn by Cernan yielded 1.24 ± 0.23 tracks/cm².⁽⁵⁾ These two detectors were processed in the same manner (2.0 hr etch). Taking into consideration the longer exposure of Apollo 10, the data still implies that the cosmic ray heavy ion flux was somewhat higher during the latter mission. The increase in flux is presumably accounted for by the decrease in the degree of solar modulation. The Apollo 8 result is in agreement with the work of Comstock and coworkers⁽⁶⁾ who used the Lexan Apollo 8 and 12 helmets to record $Z \geq 10$ particles. For Apollo 8 and 12 helmets, they found a track fluence of 0.56 ± 0.053 and 1.48 ± 0.15 tracks/cm², respectively. However, since their processing and scanning procedures differed significantly from that of ours, the agreement for Apollo 8 track fluence appears fortuitous.

In order to make track fluence inter-comparisons between various missions meaningful, an effort was made to standardize as many processing parameters as possible. One,

previously unprocessed detector, from each mission was selected. All detectors were simultaneously UV irradiated, and processed at one time. Each detector was scanned, independently, by at least two different observers. Only tracks which appeared on both surfaces of the Lexan detector were recorded. This somewhat arbitrary but rigid criterion automatically insured that only primary, $Z \geq 10$ particle exposures are intercompared. It should be noted that this criterion differs from that used in references 4 and 5. In the past, all tracks of primary particles were recorded. However, the exposed detectors contain short tracks, the majority of which are energetic, proton induced recoils with $3 \leq Z \leq 8$. Without a complete charge identification of every track found, these are difficult to separate from the short tracks produced by some of the primary particles. Thus it is difficult to separate the low energy, $3 \leq Z \leq 8$ primary particles, from the same charge group of energetic secondaries.

The track fluences found in this manner, corrected for individual scanning efficiency, are shown in Table II. These numbers represent the total track fluence for the mission arising from the $Z \geq 10$ particle component. It is observed that the Apollo 8 fluence still lies significantly below that of the other missions. Therefore the increase in the heavy cosmic ray particle flux as recorded by subsequent missions, appears to be real.

The data in Table II are about a factor of 3 higher than that previously reported for the fluence of $Z \geq 10$ particles.^(4,5) This arises from the fact that lower LET, $Z \geq 10$ particle

tracks are now observable; it is not due to a contribution from the $Z < 10$ component. As previously stated, tracks due to $Z < 10$ particles were systematically excluded from these measurements. This means that the previously reported results⁽⁴⁻⁶⁾ represent only a fraction of the total fluence of $Z \geq 10$ particle tracks observable with Lexan detectors etched for 8 hours.

TABLE II
Results of one detector from each flight, Apollo 8 - 13

Mission	Mission Type	Date and Duration	Detector Location	Track Fluence ($Z \geq 10$) (no./cm ²)
Apollo VIII	Lunar Orbiting	12/21/68 147 hours	M. H. Anders, LEM, ankle (3C)	2.0 ± 0.5
Apollo IX	Earth Orbiting	3/3/69 241 hours	J. McDivitt, CSM, ankle (6A)	none
Apollo X	Lunar Orbiting	5/18/69 192 hours	E. Cernan, LEM, ankle (C7)	3.4 ± 0.5
Apollo XI	Lunar Landing	7/16/69 199 hours	M. Collins, CSM, ankle (2C)	3.1 ± 0.6
Apollo XII	Lunar Landing	11/14/69 244.5 hours	R. Gordon, CSM, ankle (2C)	4.5 ± 0.8
Apollo XIII	Lunar Flyby	4/11/70 143 hours	F. Haise, LEM, ankle (3C)	2.9 ± 0.6

After charge identification of tracks, and taking into consideration the natural bias of the detectors toward registration of the higher Z particles, the density of enders (stopping particles) as an integral spectrum in charge number, Z , can be computed. An example, for Apollo 11, is shown in Table III, and Figure 3. Here, the number of stopping particles/cm³ with $Z \geq Z_0$ are given as a function of Z_0 . For all particles Z has been taken to have the even value most consistent with the track measurements. The errors indicated are those due to counting statistics. Primary particles with $6 \leq Z < 10$ are

also included. In order to eliminate low energy recoil particles, particles with $Z < 6$ were excluded. The stopping particle densities in Lexan can be converted to values appropriate for tissue by multiplying by the density of tissue ($\sim 1 \text{ g/cm}^3$) and dividing by the density of Lexan (1.17 g/cm^3).

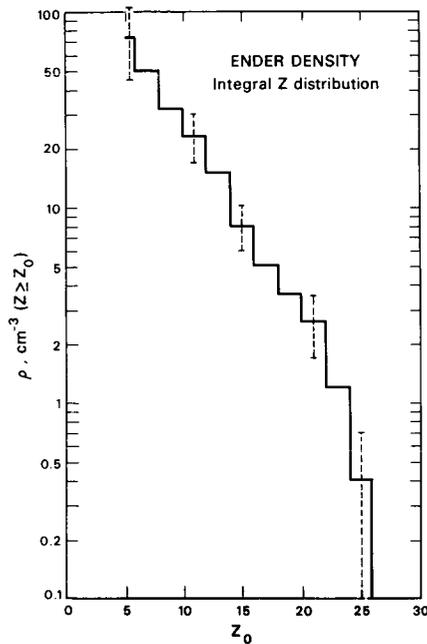


Figure 3. Stopping particle density in Lexan, $\rho(z>Z_0)$ (particles/cm³) with $Z > Z_0$ for Apollo 11 detector (2C).

Perhaps the biologically most meaningful expression of the data is a particle LET spectrum. An example, for Apollo 11, (2C) detector is shown in Figure 4. This is an integral LET spectrum giving the number of particles/cm² - ster. with $\text{LET} > \text{LET}_0$. The effective LET cutoff value is $\text{LET}_c = 0.177 \text{ MeV}/\mu$. The errors indicated are those due to counting statistics. The LET spectra measurements with Lexan can be extended to higher LET values by either reducing the degree of detector sensitization, or by using unsensitized material. However, for lower LET values, other, more sensitive detectors must be utilized.

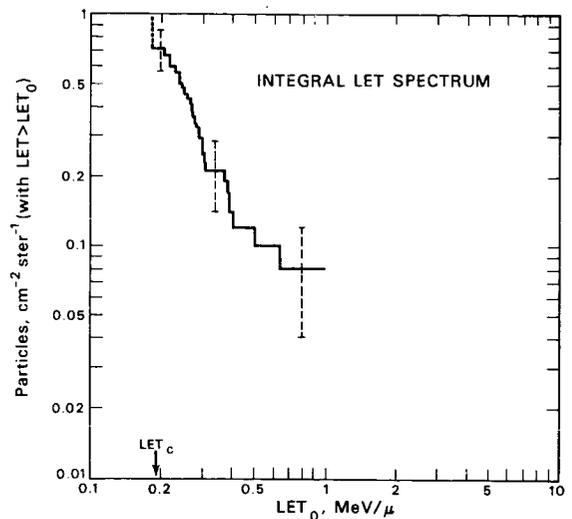


Figure 4. Integral LET spectrum, particles/cm²-ster with $\text{LET} > \text{LET}_0$, as a function of LET_0 (MeV/micron) for Apollo 11 detector (2C).

SUMMARY AND CONCLUSIONS

The most interesting results and observations obtained to date with Lexan detectors can be summarized as follows:

1. Comparison of track fluences measured on Apollo 10-13 as compared with Apollo 8 mission, suggests an increase in the high Z cosmic ray flux. This increase may be due to a decrease in the degree of solar modulation.

2. Although the detectors are heavily biased toward the higher Z particles, fewer $Z = 26$ (Fe) particles are observed than expected as compared with lighter particles. This suggests a break up of Fe particles in passage through the spacecraft shielding. Thus the Z spectrum inside the spacecraft is shifted toward the lighter particles.

3. Only the fraction of the $Z \geq 10$ particle flux that corresponds to essentially stopping particles are recorded. These are the highest LET particles (and probably the most biologically significant) that either stop in the detector or the astronaut.

4. From these measurements, stopping particle densities in the form of integral Z distributions can be obtained.

5. High Z particle, integral LET spectra can be computed.

6. Preliminary data indicates that considerable variations exist in the recorded high Z track fluences as a function of detector location on the astronaut's body.

7. The frequency of the light flash phenomenon reported by the astronauts is considerably higher than the frequency with which the $Z \geq 10$, stopping particles are incident on tissue as recorded with Lexan. This implies that lower LET particles are at least partially responsible.

8. Tracks of the heavy ion recoil particles produced by the scattering (mostly inelastic) of protons are also observable in the Lexan detectors. Higher recoil track densities are observed on missions with trajectories that take the spacecraft through the intense regions of trapped protons. These heavy recoil particles may have a role in the light flash phenomenon since Tobias and coworkers have reported observing light flashes induced by beams of high energy neutrons.⁽⁷⁾ It follows then the light flashes should be observable while the spacecraft is in the earth orbit, with the frequency of events being greatest in the vicinity of the South Atlantic Anomaly.

It is interesting to compare the different response to high LET particles of nuclear photographic emulsion and of plastic track detectors. In Figures 5 and 6 are shown tracks from the Apollo 8 mission.⁽⁴⁾ In Figure 5 is shown a track of a $Z = 26 \pm 2$ particle traversing from left to right a G.5 emulsion and an adjacent

plastic detector. The nearly equal lengths of the etch cones imply a fast particle. In Figure 6 is shown a track of a $Z = 23 \pm 1$ nucleus traversing from left to right a G.5 emulsion and two adjacent plastics. The observed rapid change in the lengths of the etch cones implies a slow, stopping particle. From the similarity of the two tracks in the nuclear emulsion, it is clear that in this detector a measurement of the change in the particles ionization rate (over these short ranges) is not feasible.

In order to obtain greater accuracy in the measurement of the high LET particle fluences, stopping particle densities, and LET spectra, and also to extend the measurements in both the Z and the energy, a considerably larger stack of Lexan was flown on Apollo 14. This stack was composed of some 100, 10 X 10 cm sheets of Lexan of the same batch as used on the previous missions. Positioned against the side of the spacecraft the stack remained stationary during the flight. Since the amount of data obtainable is approximately proportional to the volume-exposure time factor, this experiment should result in about a factor of 50 increase in the number of recorded tracks with a corresponding increase in the accuracy of the measured statistics.

For measurement of lower LET particles such as the $2 \leq Z \leq 9$ group or the more energetic $Z \geq 10$ group, more sensitive detectors are needed. Of the plastic detectors, cellulose triacetate, and cellulose nitrate have sensitivities which fall in this range. However, further development of these detectors is necessary, since considerably less is known of their behavior and response as compared to that of Lexan.

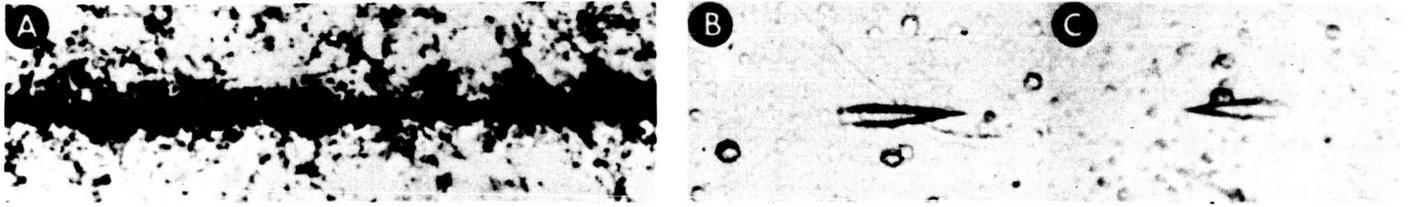


Figure 5. A track of a fast, $Z = 26 \pm 2$ particle in a detector from the Apollo 8 mission: (a) in Ilford G.5 nuclear emulsion; (b) entrance track in adjacent Lexan sheet; (c) exit track in Lexan.

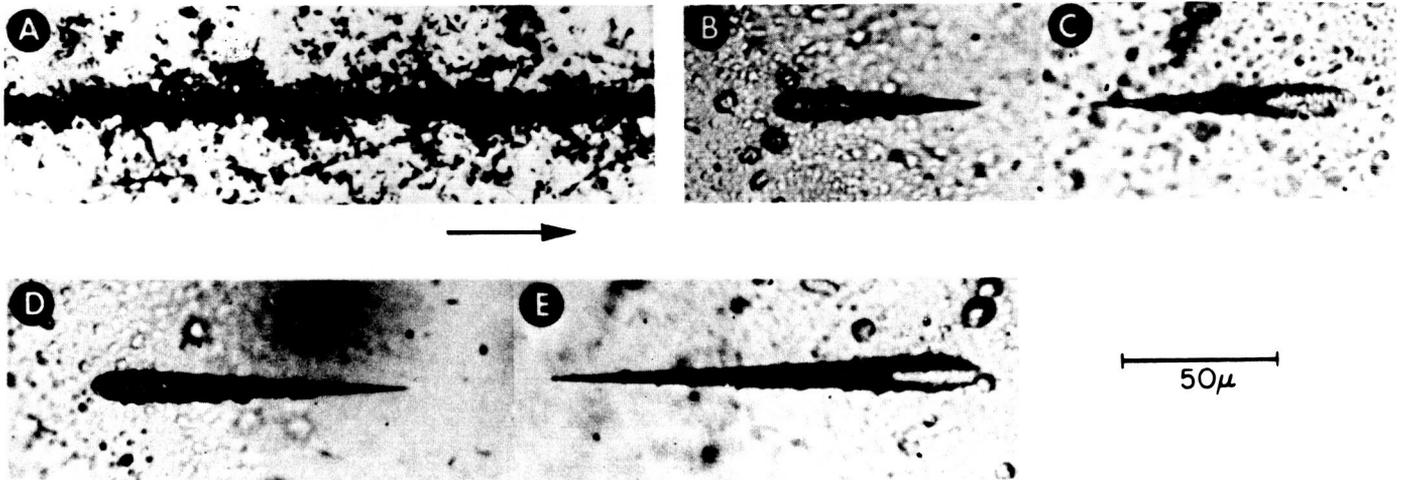


Figure 6. A track of a stopping $Z = 23 \pm 1$ particle in a detector from Apollo 8 mission: (a) in G.5 emulsion; (b-c) and (d-e) in two adjacent plastics.

TABLE III

Stopping particle density in Lexan $\rho(z \geq z_0)$ (particles/cm³ with $Z \geq Z_0$)
for Apollo 11 detector (2C).

Z_0	$\rho(z \geq z_0)$
6	74 ± 29
8	50 ± 16
10	32 ± 9
12	23 ± 6
14	15 ± 4
16	8 ± 2
18	5.0 ± 1.4
20	3.6 ± 1.1
22	2.6 ± 0.9
24	1.2 ± 0.5
26	0.4 ± 0.3

REFERENCES

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